CFD Simulation of Mechanical Draft Tube Mixing in Anaerobic Digester Tanks

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ABSTRACT: Computational Fluid Dynamics (CFD) was used to simulate the mixing characteristics of four different anaerobic digester tanks (13.7, 21.3, 30.5, and 33.5 m) equipped with single and multiple draft impeller tube mixers. Rates of mixing of step and slug injection of tracers were calculated from which digester volume turnover time (DVTT), mixture diffusion time (MDT), and hydraulic retention time (HRT) could be calculated. Washout characteristics were compared to analytic formulae to estimate any presence of partial mixing, dead volume, short-circuiting, plug or piston flow.

1.0 INTRODUCTION

The intent of anaerobic digestion is the destruction of volatile solids by microorganisms in the absence of oxygen. Digestion rates are primarily functions of a) solid retention time, b) hydraulic retention time, c) temperature ~ 95°F, and d) mixing**.** Environmental engineers generally agree that the key to good continuous-stirred-tank-reactor (CSTR) anaerobic digester operation is mixing. Mixing produces uniformity by reducing thermal stratification, dispersing the substrate for better contact between reactants, and reduces scum buildup in the digester. If mixing is inadequate, the efficiency of digestion is reduced.[2, 4, 6, 13]

Several “rules-of-thumb” are common among digester designers to size anaerobic digestion systems, these include:

- *Digester Volume Turnover Time* (DVTT) = (Tank volume/Pump Capacity),
- *Hydraulic Retention Time* (HRT) = (Tank volume/Sludge volume input rate),
- *Unit Power* (UP) = (Pump horsepower/Tank volume/1000), and
- *RMS Velocity Gradient* (VGT or G) = (Pump power/Tank volume/Sludge viscosity).

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DVTT is a measure of anticipated mixing capacity of the digester, HRT is an indicator of the mean reaction time[3], whereas UP and G quantify pump capacity and normalize mixing intensity based on the flow properties of the sludge. Desirable magnitudes of DVTT, HRT, UP and G are typically about 0.5-1 hr, 15-30 days, 0.2-0.3 Hp/1000 ft^3, and 50-85 s^{-1}, respectively.[1,13]

But once a system is designed, some confirmation of system mixing efficiency is often sought. In the past this has been determined by full-scale tracer methods which can be quite time-consuming and require internal placement of instrumentation and expensive test apparatus. The experimental procedures require seeding a slug of inlet sludge with tracers (Eg. lithium chloride) and inferring sludge residence time from measurements of the "wash out" of tracer concentrations within the tank and at the outlet over extended times (up to 90 days). The final results are expressed in terms of measured *Mixing Dispersion Time* (MDT, the time for the slug to mix uniformly throughout the tank such that the outlet tracer concentrations reach a maximum), a measured *Hydraulic Retention Time* (HRT, associated with the time constant for the exponential decay of outlet tracer concentrations), and the *Active Volume* (AV, ratio of nominal tank volume minus dead or inactive volume to nominal tank volume). AV is normally implied from tracer washout tests by comparing actual decay of tracers at the digester exit to analytic or ideal decay rates.[3, 4, 10, 11, 17]

Today modern Computational Fluid Dynamics (CFD) software permits the confirmation of mixing efficiencies for different digester configurations before construction,

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[3] Solid Retention Time (SRT), in days, is equal to the mass of solids in the digester divided by the solids removed; however, for digestion systems without recycle, SRT and HRT are equal.

hence, eliminating the need for expensive post-construction field tests.[8,9,14,15,17] Furthermore, this approach eliminates the painful realization a system is inefficient after installation. CFD visualization and analysis also provide an opportunity to examine alternative inlet, outlet and pump configurations. Visualization of fluid velocity vectors, streamlines and particle trajectories can help the user understand the mixing processes, and it can identify possible problems in advance. This paper will examine the mixing characteristics of four different size digester tanks equipped with alternate arrangements of external and internal draft tube mechanical mixers using CFD simulation methods. Resultant tank mixing behavior has been compared with analytic integral models which allow for the effects of partial mixing, dead volumes, short-circuiting, and piston flow.

2.0 COMPUTATIONAL MODEL

A CFD solution of mixing in such mixed tanks requires specification of the tank geometry, inlet, outlet, boundary and initial conditions. The solution requires the simultaneous CFD solution of the discretized mass, momentum, and energy equations.

2.1 Flow Domain and Boundary Conditions The flow domain consisted of a cylindrical tank of a given diameter and height, inlet and outlet pipes, and impeller driven draft tubes placed around the perimeter or within the tank. No-slip boundary conditions were imposed on all wall surfaces. At the inlet a constant flow rate was specified, and the outlet was treated as a mass flow boundary. Pumps in the draft tubes were simulated as virtual fan areas across which a pressure rise of ~6500 pascals was adjusted until a desired draft - tube flow rate was obtained.

2.2 Computer Code The commercial CFD code Fluent, version 6.3, developed by Fluent/ANSYS was used for all calculations. The code uses a finite volume method based on discretization of the governing differential equations.

2.3 Turbulence Model The standard κ-ε turbulence model was used for all calculations with standard wall function approximations near walls; hence, additional transport equations for turbulent kinetic energy (κ) and eddy dissipation (ε) were solved for these quantities. The standard κ-ε model has been successfully used by many researchers for similar mixing problems.[8, 9, 15] When draft-tube Reynolds number exceeded 10,000 previous calculations agreed well with experiments.[15] In the current analysis the minimum draft-tube Reynolds numbers always exceeded 285,000.

2.4 Computational Grids The geometry of the tank was modeled in GAMBIT which discretized the domain into an unstructured array of tetrahedral mesh elements. Total cells ranged between 775,000 to 1,640,000. Elements were concentrated in regions of walls, inside draft tubes, and near flow inlet and flow outlet to preserve details of velocity shear and increased turbulence.

2.5 Solver A 3-D, implicit, pressure based, segregated, steady solver algorithm was used for predicting the velocity and turbulence fields, and a time dependent mode was used for predicting sludge concentrations. The SIMPLE pressure-velocity coupling method was specified, and second-order upwind discretization molecules were used for all discretized terms. Under-relaxation factors were 0.3, 1.0, 1.0, 0.7, 0.8, and 0.8 for pressure, density, body forces, momentum, kinetic energy, and dissipation, respectively. The solution strategy for the large tanks was to initially solve for the steady-state flow circulation produced by the draft tubes and inlet flow, and then introduce a step change in inlet concentration or introduce a slug of tracer at time zero in a time dependent evaluation of mixing. During the solution for mixing, solutions for the flow field were held constant.

The inlet sludge was assumed diluted such that the density of the solid-water suspension and its absolute viscosity approximate the characteristics of water. Low shear measurements of actual sludge suggest higher apparent viscosities are possible due to non-Newtonian effects, but given the property uncertainties many researchers use the lower viscosity of water when active mixing occurs.[5, 12]

2.6 Convergence Criteria The method to judge convergence was to monitor the magnitude of scaled residuals. Residuals are defined as the imbalance in each conservation equation following each iteration. The solutions were said to have converged when the scaled residuals go below values of 10^{-4}.

3.0 SMALL TANK VALIDATION EXERCISE

In 1959 Cholette and Cloutier derived integral models which described the time dependent tank mixing in idealized reactors when influenced by imperfections in the mixing process.[3, 4] They created algebraic expressions which included the deleterious effects of partial mixing, short-circuiting of inlet flow directly to the outlet, the effects of plug (or piston) flow which ejects unmixed fluid from the outlet, and the impact of dead or non-participant regions on the outlet concentrations. Later Wolf and Resnick proposed a generalized washout equation based on these ideas,[17] where

$$\boxed{C_{SO}(t)/C_O = \exp\left\{-\frac{(1-f)}{ar(1-d)T_{HRT}}\left[t - L - \frac{p(1-d)rT_{HRT}}{(1-f)} + \beta ar(1-d)T_{HRT}\right]\right\}} \qquad \text{Eq (1)}$$

where a = fraction of effective volume perfectly mixed
d = fraction of volume that is dead or non-participant
f = fraction of flow rate that short-circuits with infinite speed to outlet
p = fraction of effective volume that sees plug (or piston) flow
r = residence time correction factor associated with measurement errors in V or v
L = lag time of instrumentation [sec]
t = time [sec]
T_{HRT} = hydraulic return time = V/v
V = total system volume [L^3]
v = inlet/outlet flowrate [L^3/T]

$$\beta = -\frac{\ln(1-f)}{(1-f)}, \text{ and as } f \to 0,\ \beta \to 0$$

One should note that with so many variables, it is sometimes difficult to differentiate between effects of dead space, d, measurement error, r, and partial mixing, a, when f ~ p are nearly zero, especially when mixing efficiency is near ideal. Indeed, it is not unusual for curve fitting to produce small but negative dead space volumes, which is obviously not physical. Alternatively dad zones can be found by calculating the fractional volume of the cells with very low liquid velocities. Veviskar and Al-Dahhan suggested that regions with velocities less than 5% of the maximum velocities could be considered stagnant or inactive regions.[14] One advantage of this method is it does not permit negative dead volumes, but a disadvantage is that it does not relate directly to the washout equation.

A small tank experiment was performed by Cholette and Cloutier to examine the influence of partial mixing and short-circuiting on tank mixing.[3] They introduced fresh water into a tank filled with a 1/20 N solution of NaCl in the configuration shown in Figure 2. After running the agitator for some time at a fixed speed to allow the mixing pattern to fully develop, fresh water was introduced suddenly at a rate of 4.35 liters/min (1.15 gpm). Hydraulic retention time (HRT) for this experiment was 1.56 hrs. They measured outlet concentrations every five minutes and plotted them versus time on semi-logarithmic paper. Axis intercepts and line slopes were fit to the data to define coefficients related to partial mixing, a, and short-circuit behavior, f, in Equation 1. Mixing intensity was qualitatively parameterized by the rotation rate of the mixer. At zero mixer rotation the flow was driven by only the inlet jet such that mixing parameters were f = 0.23 and a = 0.38, and when mixer operated at full speed mixing parameters approached f = 0.0 and a = 1.0.

A CFD model of the Cholette and Cloutier apparatus was constructed to validate the methodology described in Section 2.0. The domain was filled with 381,000 tetrahedral cells adapted for greatest resolution near the upper surface of the fluid and around the inlet jet and outlet pipe. The inlet to the outlet pipe was positioned to two locations below the fluid surface (Δz = 0.65 and 1.30 cm) since exact location was not provided by the authors. Calculations did not show any significant differences in results. Cases were also simulated for both laminar and turbulent mixing for the fan off case, again differences were small. The turbulence model used was the realizable kappa-epsilon model. The model was run with a pressure-based implicit unsteady solver, and residuals were set at 0.001 for flow quantities and 0.0001 for concentrations. The mixing turbine was simulated by specifying a circular fan area of 25 cm^2 with a pressure drop of Δp = 345 pascals, and tangential swirl speed of 30.5 cm/sec. The tank was filled with salt-water of density 1027 kg/m^3 (sg = 1.00292) and fresh water was injected of density 998 kg/m (sg = 1.00). Outlet and tank average salt-water concentrations were tabulated versus time. Results are reported in Figure 3 for the cases with no fan mixing and strong fan mixing.

When fresh water is introduced into the mildly turbulent salt-water filled tank, the mixing is inhibited by the vertical density gradient induced by the two fluids. The fresh water rises directly to the surface spreads radially, and almost immediately is entrained into the outlet producing significant short-circuit behavior (Figure 4a). The stratification inhibits vertical mixing such that particle tracks are limited to the upper 1/3 of the tank. (Figure 5a). The integral parameters, a and f equal 0.65 and 0.25, respectively. This corresponds to behavior Cholette and Cloutier reported of 0.63±0.05 and 0.20±0.05 for a turbine rotating at 140 rpm. When the numerical fan was set to enhance mixing (Δp=345 pascals, $V_{tangential}$ = 30.5 cm/s), density stratification was eliminated, the outflow removed fluid mixed over the entire tank volume (Figure 5b), and particle tracks filled the entire volume before exiting through the outflow pipe (Figure 5b). The resultant integral parameters, a and f equal 1.0 and 0.0 respectively. These equal the values found by Cholette and Cloutier when their turbine rotation exceeded 215 rpm. Notice in Figure 3 that the outlet concentration ratio Cso/Co_{CFD} is contiguous with C_{tank}/Co_{CFD} which indicates the outflow is releasing fully mixed tank fluids. Parameters calculated for various fan mixing intensities are shown in Figure 6.

A caveat should be mentioned concerning the comparisons of actual tank mixing performance in the Cholette and Cloutier experiment with the analytic model found in Equation 1. Detailed mixing deviates from the simplified idealized assumptions inherent in this equation. As noted in Figure 3 short-circuiting takes finite time to exhibit its influence, and the initial inhibition to mixing due to stratification decreases as time proceeds which results in the increase in magnitude of the partial mixing parameter, a, with time.

3.0 FULL SIZE TANK ANALYSIS AND RESULTS

Mixing during unit operations can be achieved by impellers, introduction of gas jets, or the use of mechanical draft-tube mixing. During draft-tube mixing part of the liquid from the tank is re-circulated into the tank at high velocities through draft tubes with the help of pumps and nozzles. The resulting fluid jet entrains surrounding fluid and creates a flow pattern that circulates radially and circumferentially about the tank from top to bottom. Draft tubes are categorized as external (EDT) when the pump is outside the tank and internal (IDT) when the pump and tube are within the tank volume. Tube nozzles are generally directed at an angle to the radius to improve mixing efficiency.

Recently, Wasewar and Sarathi used CFD modeling to determine optimum nozzle geometries.[15] They also reviewed some nine previous studies that used cfd codes to evaluate nozzle mixed tanks. They used the commercial CFD code Fluent 6.2, with 50,000-80,000 tetrahedral cells over the calculation domain, the SIMPLE and PISO algorithms for steady and transient pressure-velocity coupling, the segregated solver algorithm, and the standard kappa-epsilon turbulence model. They concluded their CFD simulations faithfully reproduced experimental measurements for cases where the draft-tube Reynolds number exceeded 10,000. Since their calculations were limited to tanks approximately 0.5 m diameter and 0.5 m high with jet diameters of 0.01 m, it was considered worthwhile to present calculations here that considered full size tanks in actual application configurations.

A set of four different tank and draft tube geometries were examined to provide a range of performance data concerning full size tanks with different draft tube arrangements. The geometry, pump and flow characteristics, and performance parameters are displayed in Figure 7 and Table 1. Tank volumes range from 1k to 10k m^3 (293 k to 265 M gallon) capacity, draft tubes numbered 1, 4 and 5 in various EDT and IDT arrangements, and nominal draft tube flow rates varied from 28 to 47 m^3 /min/tube (7,500 to12,500 gpm/tube) with sludge inlet/outlet rates set to 0.38 cubic m/min (100 gpm). Sludge exited the tank from a pipe located at tip of the conical bottoms. In all cases studied draft tube jet Reynolds numbers exceeded 285,000.

3.1 <u>Model 1: 30.5 m Diameter Tank with 4 External Draft Tubes</u> This tank was designed to produce a nominal HRT = 15.2 days. The sludge was introduced into the tank at a level 1.5 m below the fluid surface midway between two adjacent EDT positions through a 25.4

cm diameter pipe mounted on the side wall. Inlets and outlets to the draft tubes were oriented at 45° to produce a clockwise flow when viewed from above. Mixing was tested after the tank system reached a steady state condition, a constant magnitude of tracer was added to the inlet pipe and the subsequent mixing and exit of the tracer from the outlet was recorded.

Plots of velocity magnitude, V, and turbulence intensity, $TI = (u_i'^2)^{½} / V_{ref}$, across the tank diameter at five depths are shown in Figure 8. The draft tube jets induce a rotational circulation that is constant with depth, zero at tank center and maximum near the tank walls (Figure 9). Turbulence is maximum in the high shear regions surrounding the jets and close to the walls, and turbulence persists across the tank center (Figure 10). Paired Figures 11 & 12 and 13 & 14, display the pathlines and particle tracks following tracers emitted from the sludge inlet and draft tube fans, respectively. Pathlines follow circular paths associated with the average fluid velocity motion, whereas particle tracks display erratic mixing about the pathlines resulting from local turbulence disturbances. Mixing occurs as a result of fluid dispersion associated with the particle tracks. Mixing associated with the EDT nozzles distributes circumferentially, fluid from top to bottom, and from tank center to walls very effectively. Multiple draft tubes help turn the fluid over as they withdraw fluid from the tank top and reintroduce it at the tank bottom. A mixing particle traverses the tank many times before it is removed at the oulet at the bottom of the tank cone.

To evaluate the Hydraulic Retention Time and the efficiency of the mixing geometry a constant quantity of tracer was introduced at the sludge inlet starting at time zero. Figures 15, 16, and 17 display the progressive growth of mixing at three typical times as the tracer spread across the tank. Initially the tracer plume grows along the wall in a cigar shaped plume, but then tracer is drawn out of the plume and reintroduced by the nozzles near the tank bottom, which produces four additional circular plumes. These plumes eventually coalesce, mix, and the level of concentration increases dynamically. Since, the tank outlet is at the bottom of the tank cone, concentrations tend to appear symmetric about the tank center. Concentrations surfaces are progressively drawn downward and swept from the outlet until the tank (at long times) is completely filled with the tracer at its inlet concentration.

The time variation of tracer concentration at the sludge outlet relative to sludge inlet, C_{SO}/C_{SI} CFD, was recorded during the computations and is plotted in Figure 18. The same plot also includes the CFD calculated tank average concentrations, C_{tank}/C_{SI} CFD. The line C_{tank}/C_{SI} Analytic is calculated from the expression, $C_{Tank} / C_{SI} = \exp\left[- {}^{t}\!/\!_{HRT}\right]$.......(2). This expression lies directly over the C_{tank}/C_{SI} values computed by CFD, which confirms that the calculation obeys the species conservation equation. The fit of this equation to the data also provides the value for tank Model 1 of HRT = 17.88. As noted in Table 1, the nominal value of HRT for the actual CFD calculated conditions was 17.7, which agrees closely to the CFD generated value.

If the mixing was ideal (instantaneous mixing of the tracer over the entire tank) then the sludge outlet concentration would also follow this line. Note that C_{SO}/C_{SI} CFD initially lags the idealized mixing curve. This may be due to a number of real phenomena discussed earlier in Section 3.0, and considered in the analytic expression Equation 1. For the Model 1 tank the deviation reflects the finite mixing rate and finite travel time for the tracer between the sludge inlet and the sludge outlet. As a result initial fluid passing out of the tank is fluid displaced out by inlet fluid in a piston or plug-flow manner. Equation 1 with the coefficients p = 0.0007 and a = 0.9993 is shown as curve C_{SO}/C_{SI} Piston & Partial Mix. Alternatively, one might identify deviations from ideal performance as a dead volume issue; and, using the method of fractional volumes with velocities less than 5% of the maximum as suggested by Veviskar and Al-Dahhan, one obtains d ~ 0.0008 from the CFD predicted velocity fields.[15] This tank design produces excellent fluid mixing, and the deviation of the coefficients from 0 and 1.0, respectively, are insignificant.

3.2 Model 2: 13.7 m Diameter Tank with 1 External Draft Tube This much smaller tank was designed to produce a nominal HRT = 2.03 days. It has a single EDT, but sludge inlet flow rate and draft tube dimensions were identical to Model 1. The asymmetric location of a single draft tube may be expected to produce non-symmetric flow patterns. Nonetheless, the central bottom exit and the round tank tend to center the flow patterns (See Figures 19, 20 and 21). However, as shown in Figure 21, a slightly less mixed region hangs above the outlet, and higher tracer concentrations exit the outflow before this region is fully assimilated into the tank. The effect of this "cloud" of less-well-mixed fluid is to produce a fit for Equation 1 with coefficients p = 0.008 and a = 0.992 as shown in Figure 22. These deviations from 0 and 1 are also small, and can effectively be ignored. The calculated HRT value equals 2.04 days, which compares well with the nominal value of 2.03 days.

3.3 Model 3: 21.3 m Diameter Tank with 3 External and 1 Internal Draft Tubes

This tank is larger than Model 1, has five rather than four draft tubes, and all tubes are internally mounted. The four outer IDT tubes draw fluid inward radially at the tank top and jet the fluid out near the bottom at a 45° angle which induces clockwise rotation. The center IDT sucks fluid radially inward from the bottom of the tank and ejects it radially outward at the top. Thus, fluid which might initially tend to exit the tank in an untimely manner is drawn back into the mixing merry-go-round. Figures 23, 24, and 25 display the time varying concentration surfaces for Model 3. Figure 26 reports the time varying behavior of the outlet concentrations. The predicted magnitude of HRT =18.4 days exactly equals the nominal value based on tank volume and sludge inlet flow rate. The best fit coefficient values for Equation 1 were p = 0.0013 and a = 0.9987. Thus, there is essentially zero dead volume and the fractional active volume is one.

3.4 <u>Model 4: 33.5 m Diameter Tank with 4 Internal Draft Tubes</u> Finally, we examined a medium size tank part way between the tank diameters of Model 1 and 4, but with three EDT tubes and one central IDT. Again the EDT tubes draw off surface fluid and reinject it at the tank bottom, and the central IDT lifts bottom fluid up to spread it outward radially at the tank top. Figures 27, 28, and 29 display the developing concentration surfaces with time. In the later mixing stages the surfaces seem to burst upwards and outwards around the central IDT like a flower in bloom. The CFD calculated HRT value equals 4.98 days, versus the nominal value of 5.0 days. Equation 1 coefficients were p = 0.004 and a = 0.996 (Figure 30).

4.0 SUMMARY OF PERFORMANCE OF DIFFERENT TANK CONFIGURATIONS

Exploration of the small mixing tank studied by Cholette and Cloutier provided an opportunity to explore the nuances of CFD simulation of mixing phenomena in CSTR systems. It was noted that tank mixing may deviate from ideal behavior for a variety of reasons associated with placement of inlets, outlets, stratification, and tank geometry. The presence of even a slight amount of density difference between the mixing fluids (SG =

1.0029 vs 1.000) was determined to strongly influence the progression of mixing. Uncertainties about the actual test configuration and measurement methods can also influence how well CFD simulations and experimental data agree. The CFD simulations of the Cholette and Cloutier tank reproduced the gross characteristics of low-turbulence and fan-mixed circulations; however, the agreement was not exact, and this author doubts if agreement can be improved given missing details about experimental uncertainty and nuances of the tank geometry (exact outlet placement, mixer characteristics). Nonetheless, the exercise provided the tools and confidence to explore full-scale anaerobic digester tank conigurations.

Four likely configurations of mixing tanks were examined. The tanks varied in size, combinations of EDT and IDT mixers, and draft tube configurations. These tanks nominal characteristics fall within the range recommended by ASCE and WEF design manuals. A summary of tank performance is available in Table 2. Nominal and calculated HRT values were in good agreement. All the tank configurations considered produced excellent mixing without any evidence of short-circuiting, dead volumes, significant partial mixing, or plug flow. The analysis was performed using conventional and typical CFD software, readily available to the practicing engineer, and its completion was significantly more efficient than post-construction field tests.

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FIGURE TITLES:

1. Schematic of idealized mixing processes including effects of partial mixing, short-circuiting, piston flow, and dead volume. Symbols are defined with the generalized mixing relation, Section 3.0.
2. Experimental mixing apparatus (Cholette and Cloutier, 1959)3
3. CFD simulation of Cholette and Cloutier tank mixing experiment. Two cases a) mild tank turbulence present initially and b) intense fan mixing present during test.

4a. Fluid density (kg/m^3) for low mixing case at t = 506 sec.

4b. Fluid density (kg/m^3) for high mixing case at t = 5355 sec.

5a. Particle tracks for low mix case, colored by residence time (sec) at t = 506 sec.

5b. Particle tracks for high mix case, colored by residence time (sec) at t = 5355 sec.

6. Parameters for mixing model (Equation 1) fit to Cholette & Cloutier, 1959, experiment, and their comparison to CFD simulations.
7. Geometry and draft tube configuration for full size model tanks studied.
8. Radial velocity and turbulent Intensity profiles at various levels within the Model No. 1 Anaerobic Digester.
9. Velocity magnitude contours within Model 1.
10. Turbulence intensity contours within Model 1.
11. Pathlines emitted from sludge inlet after t = 15 min for Model 1.
12. Particle tracks emitted from sludge inlet after t = 15 min for Model 1.
13. Pathlines emited from draft tube pump after t = 15 min for Model 1.
14. Particle tracks emitted from draft tube pump after t = 15 min for Model 1.
15. Concentration surfaces after mixing for 15 min. Release of tracer from sludge inlet, Model 1.
16. Concentration surfaces after mixing for 25 min. Release of tracer from sludge inlet, Model 1.
17. Concentration surfaces after mixing for 50 min. Release of tracer from sludge inlet, Model 1.
18. Concentration changes as a result of a step addition of tracer, ω_o = 0.05 at sludge inlet, Model 1, p = 1 - a = 0.0007.
19. Concentration surfaces after mixing for 2 min. Release of tracer from sludge inlet, Model 2.

20. Concentration surfaces after mixing for 27 min. Release of tracer from sludge inlet, Model 2.

21. Concentration surfaces after mixing for 43 min. Release of tracer from sludge inlet, Model 2

22. Concentration changes as a result of a step addition of tracer, $\omega_o = 0.05$ at sludge inlet, Model 2, $p = 1 - a = 0.008$

23. Concentration surfaces after mixing for 17 min. Release of tracer from sludge inlet, Model 3.

24. Concentration surfaces after mixing for 60 min. Release of tracer from sludge inlet, Model 3.

25. Concentration surfaces after mixing for 246 min. Release of tracer from sludge inlet, Model 3.

26. Concentration changes as a result of a step addition of tracer, $\omega_o = 1.00$ at sludge inlet, Model 3, $p = 1 - a = 0.0013$.

27. Concentration surfaces after mixing for 1.7 min. Release of tracer from sludge inlet, Model 4.

28. Concentration surfaces after mixing for 27 min. Release of tracer from sludge inlet, Model 4.

29. Concentration surfaces after mixing for 34 min. Release of tracer from sludge inlet, Model 4.

30. Concentration changes as a result of a step addition of tracer, $\omega_o = 1.00$ at sludge inlet, Model 4, $p = 1 - a = 0.004$.

Table 1: Anaerobic Tank Models Examined During CFD Simulations

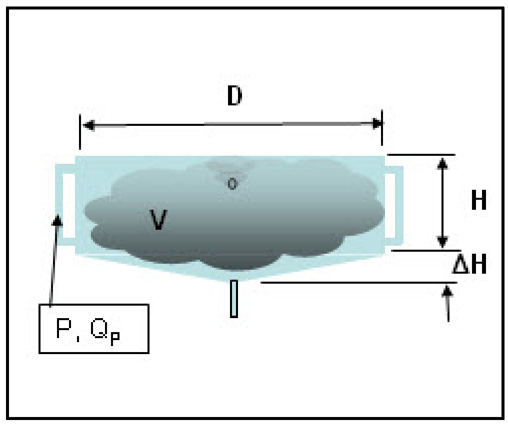
* CFD measured -- values unchanged	#1 nominal	CFD value	#2 nominal	CFD value	#3 nominal	CFD value	#4 nominal	CFD value
Tank Diameter, D (m)	30.5	--	13.7	--	33.5	--	21.3	--
Side water Depth, H (m)	10.1	--	7.3	--	10.1	--	7.3	--
Cone (floor) Depth, ΔH (m)	3.8	--	0.61	--	3.8	--	0.61	--
Mixer Quantity	4	--	1	--	5	--	4	--
Mixer Power, P (kW/mixer)	7.5	--	7.5	--	11.2	--	3.7	--
Nominal Flow Rate, Q_P (liters/min/mixer)	39,525	41,308	39,525	39,525	48,438	48,438	29,063	29,063
Sludge Inflow Rate, Q_{SI} (liters/min)	395	333	395	395	395	395	395	385
Volume of Tank, V_T (m^3)	7,375	--	1,081	--	8,823	--	2,615	--
Volume of Cone, V_c (m^3)	927	--	30	--	1,121	--	73	--
Total Volume, V (m^3)	8,301	--	1,111	--	10,045	--	2,688	--
Total Volume, V (gallons)	2,192,859	--	293,445	--	2,653,359	--	710,065	--
Power-to-Volume Ratio (W/ m^3 or hp/1000 ft^3)	4.1 (0.14)	--	6.9 (0.25)	--	6.3 (0.21)	--	5.7 (0.21)	--
Hydraulic Retention Time, HRT (days)	15.2	17.7 17.88*	2.03	2.03 2.04*	18.4	18.4 18.4*	4.9	5.0 4.98*
Turnover Rate, DVTT (min)	54	53.7	29	29	42	42	24	24
Velocity Gradient, G (sec^{-1})	71	--	97	--	88	--	88	--

$$\text{Unit Power} = \text{Power-to-Volume Ratio} = P_{Mixers} / V$$

$$\text{Digester Volume Turnover Rate, DVTT} = V / Q_{PMixers}$$

$$\text{RMS Velocity Gradient, } G = (P_{Mixers} / V / \mu)^{1/2}$$

$$\text{Hydraulic Retention Time, HRT} = V / Q_{Sludge\ In}$$



Note: The U.S. EPA and the ASCE Manual and Report on Engineering Practice No. 76 recommends a minimum Unit Power for mixing anaerobic sludge digesters of 5.2 W/m^3 (0.2 Hp/1000 ft^3) of sludge volume, a volume turnover rate, DVTT, of 30 to 45 minutes, and a velocity gradient, G, of 50 sec^{-1} or more. HRT = SRT ranges from 15 to 30 days.[16]

Table 2: Characteristics of Anaerobic Tank Models Examined During CFD Simulations

Tank #	Diameter (ft)	Mixer Quantity	HRT (days)	Active Volume, a
1	100	4	17.88	0.9993
2	45	1	2.04	0.992
3	110	5	18.40	0.9987
4	70	4	4.98	0.9960

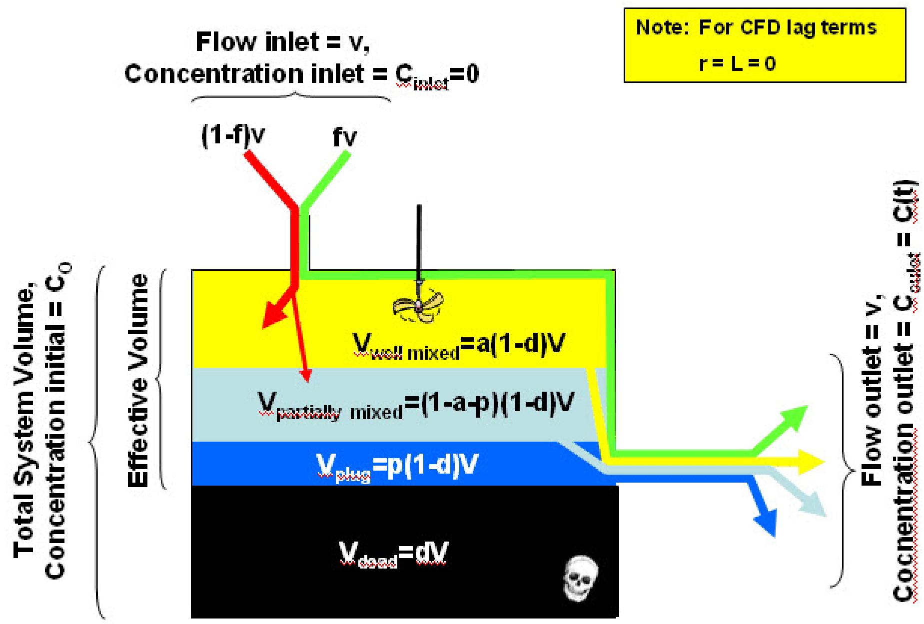


Figure 1: Schematic of idealized mixing processes including effects of partial mixing, short-circuiting, piston flow, and dead volume. Symbols are defined with the generalized mixing relation, Section 3.0.

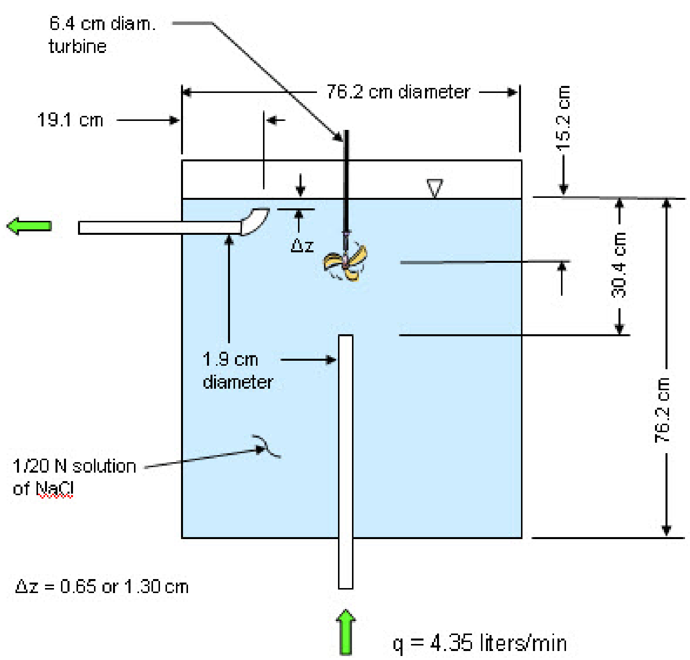


Figure 2: Experimental mixing apparatus (Cholette and Cloutier, 1959)[3]

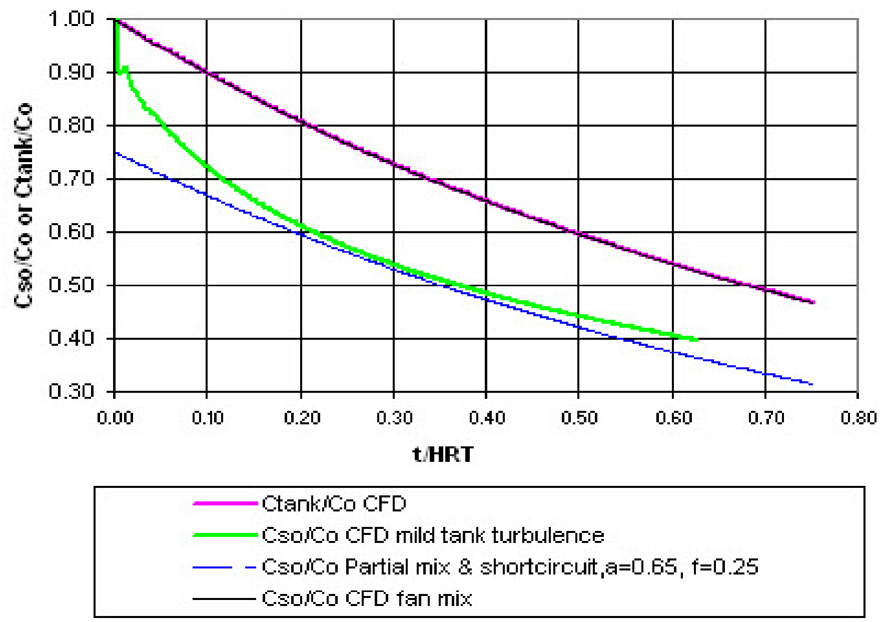


Figure 3: CFD simulation of Cholette and Cloutier tank mixing experiment. Two cases a) mild tank turbulence present initially and b) intense fan mixing present during test.

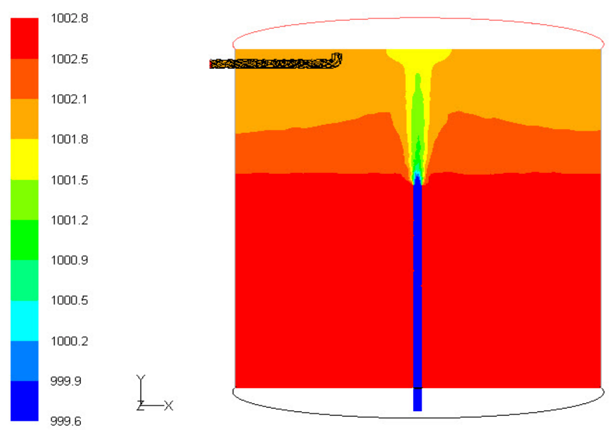


Figure 4a: Fluid density (kg/m^3) for low mixing case at t = 506 sec.

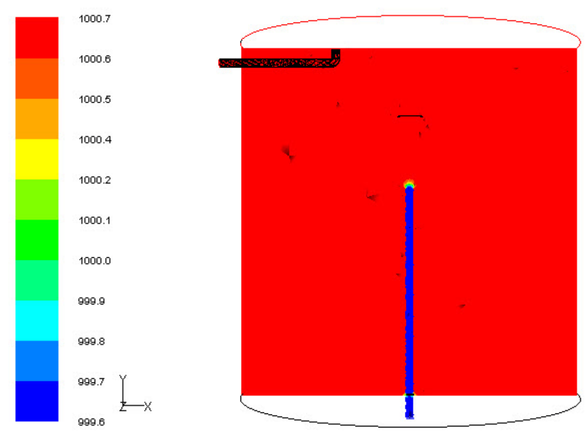


Figure 4b: Fluid density (kg/m^3) for high mixing case at t = 5355 sec.

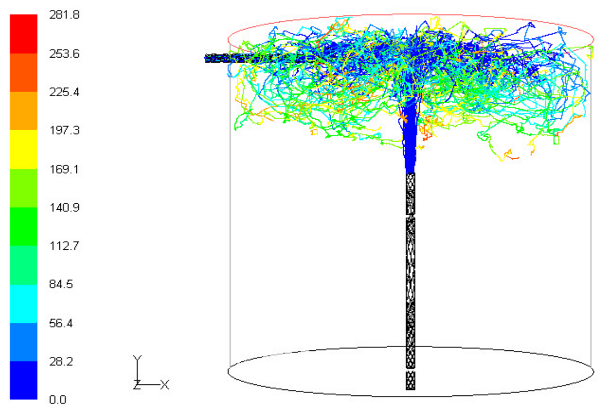


Figure 5a: Particle tracks for low mix case, colored by residence time (sec) at t = 506 sec.

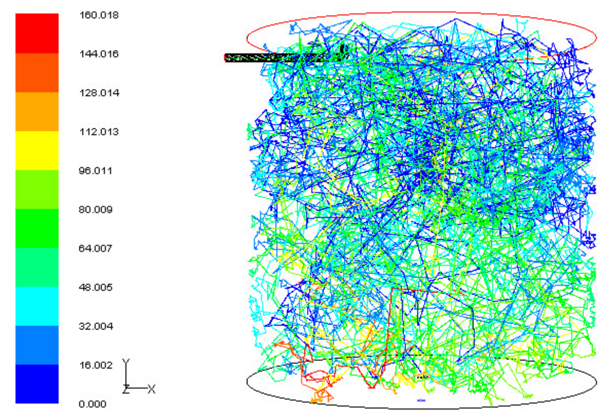


Figure 5b: Particle tracks for high mix case, colored by residence time (sec) at t = 5355 sec.

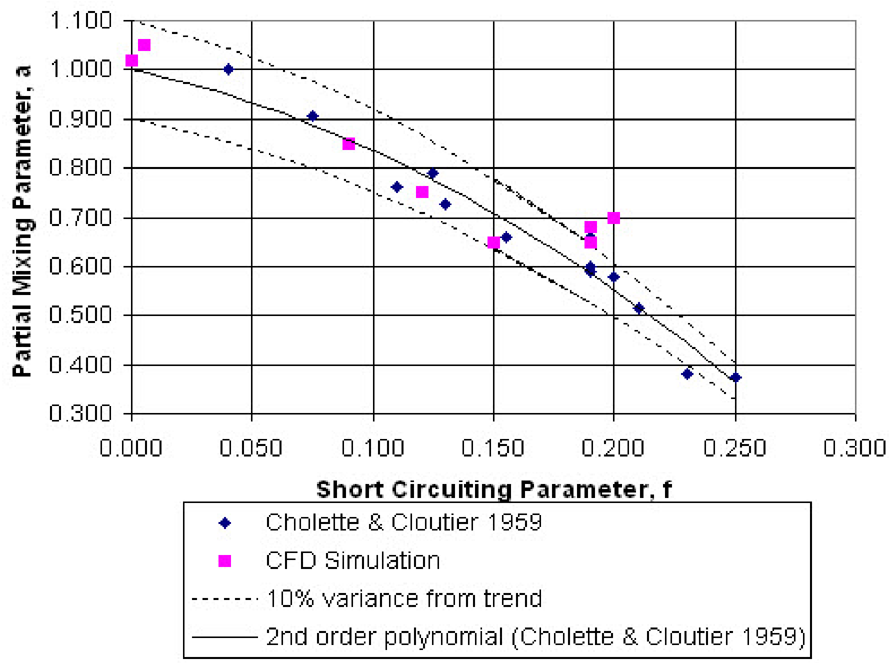


Figure 6: Parameters for mixing model (Equation 1) fit to Cholette & Cloutier, 1959, experiment, and their comparison to CFD simulations.

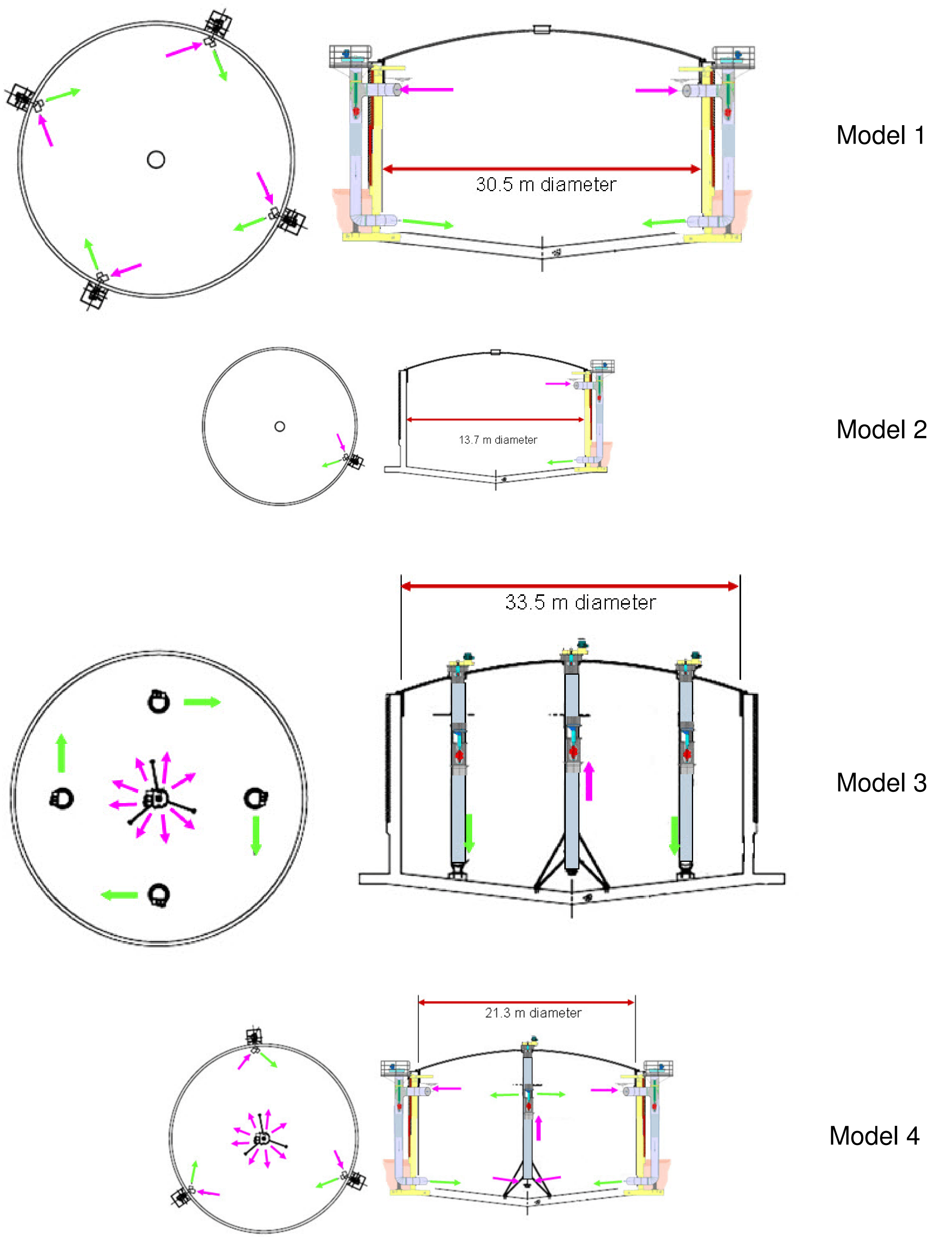


Figure 7: Geometry and draft tube configuration for full size model tanks studied.

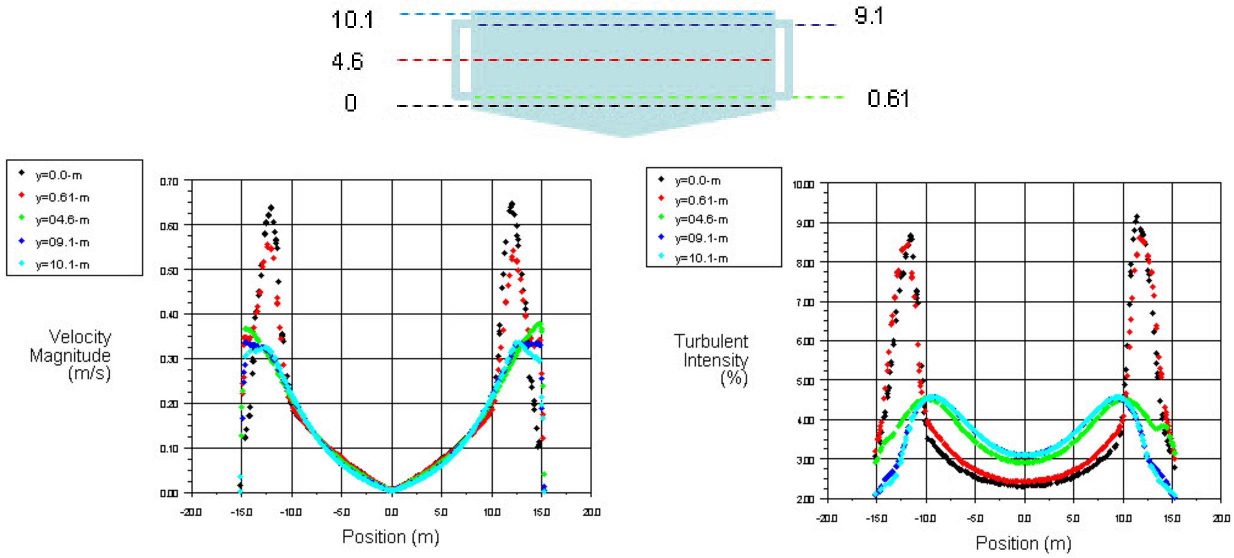


Figure 8: Radial velocity and turbulent Intensity profiles at various levels within the Model No. 1 Anaerobic Digester.

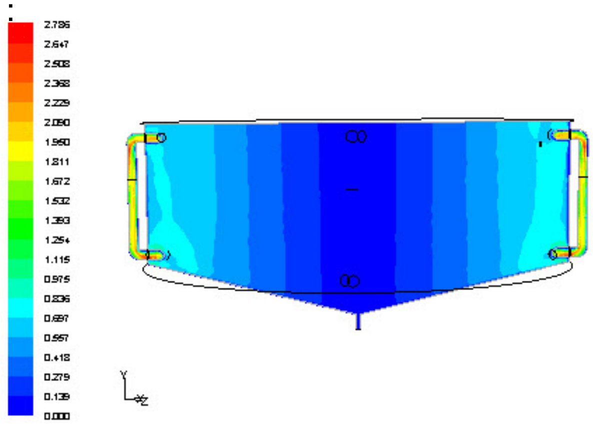


Figure 9: Velocity magnitude contours within Model 1.

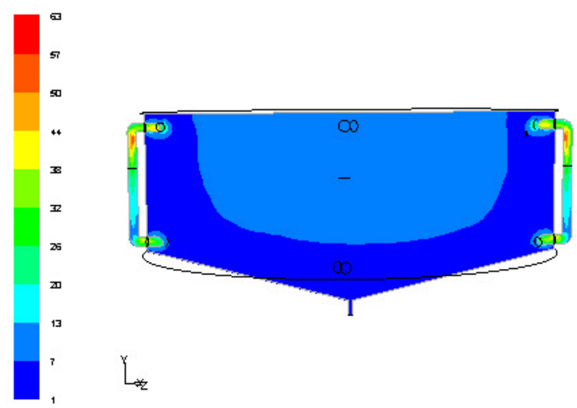


Figure 10: Turbulent intensity contours within Model 1.

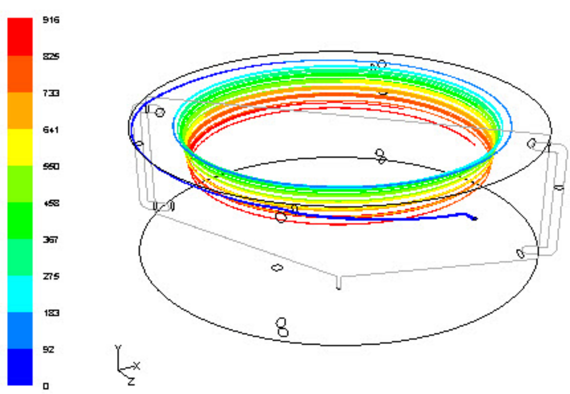


Figure 11: Pathlines emitted from sludge inlet after t = 15 min for Model 1.

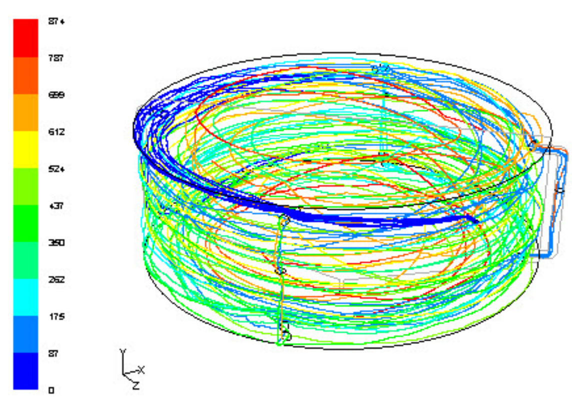


Figure 12: Particle tracks emitted from sludge inlet after t = 15 min for Model 1.

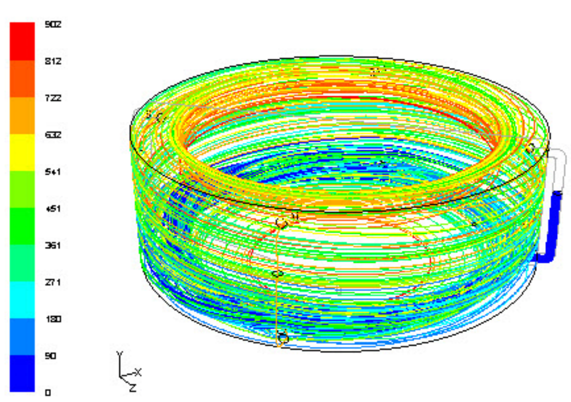


Figure 13: Pathlines emitted from draft tube pump after t = 15 min for Model 1.

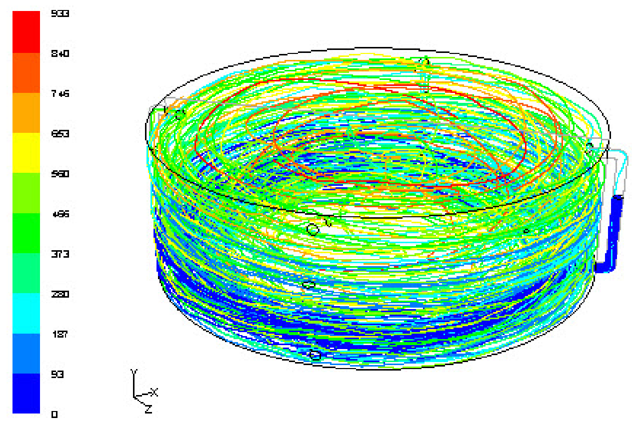


Figure 14: Particle tracks emitted from draft tube pump after t = 15 min for Model 1.

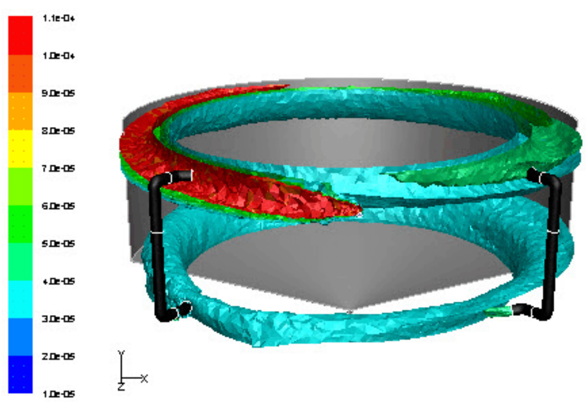


Figure 15: Concentration surfaces after mixing for 15 min. Release of tracer from sludge inlet, Model 1.

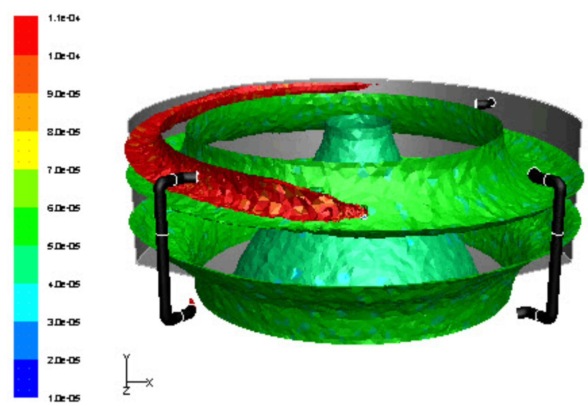


Figure 16: Concentration surfaces after mixing for 25 min. Release of tracer from sludge inlet, Model 1.

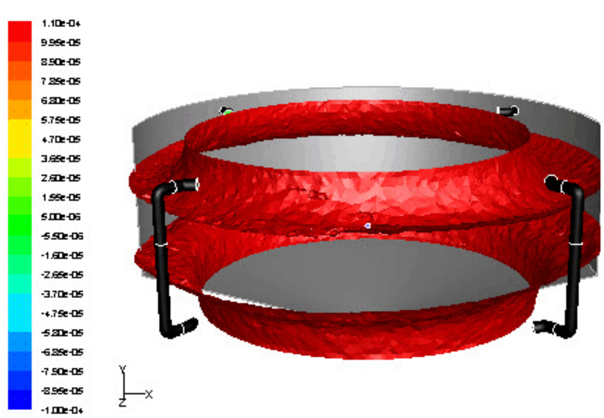


Figure 17: Concentration surfaces after mixing for 50 min. Release of tracer from sludge inlet, Model 1.

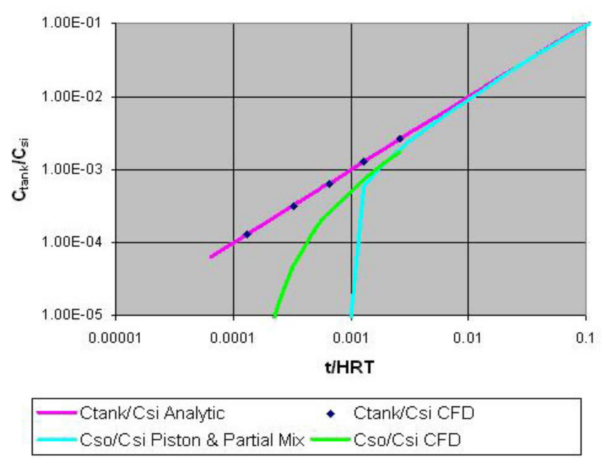


Figure 18: Concentration changes as a result of a step addition of tracer, $\omega_o = 0.05$ at sludge inlet, Model 1, p = 1 - a = 0.0007.

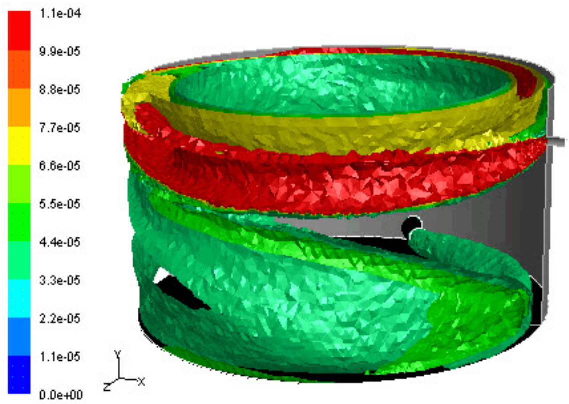


Figure 19: Concentration surfaces after mixing for 2 min. Release of tracer from sludge inlet, Model 2.

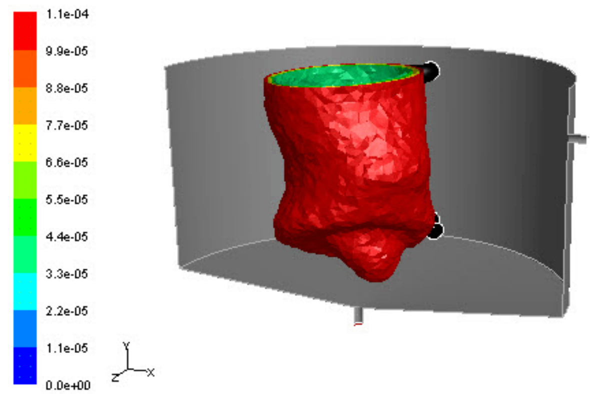


Figure 20: Concentration surfaces after mixing for 27 min. Release of tracer from sludge inlet, Model 2.

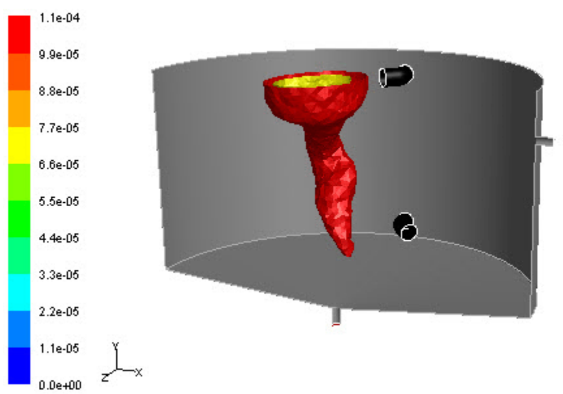


Figure 21: Concentration surfaces after mixing for 43min. Release of tracer from sludge inlet, Model 2.

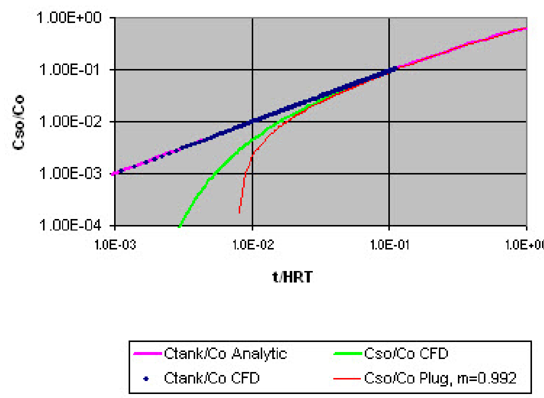


Figure 22: Concentration changes as a result of a step addition of tracer, ω_o = 0.05 at sludge inlet, Model 2, p = 1 - a = 0.008

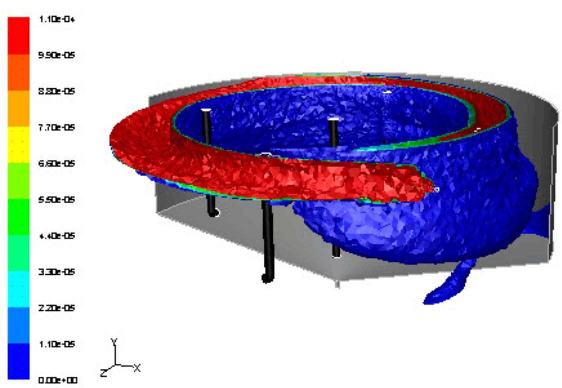


Figure 23: Concentration surfaces after mixing for 17 min. Release of tracer from sludge inlet, Model 3.

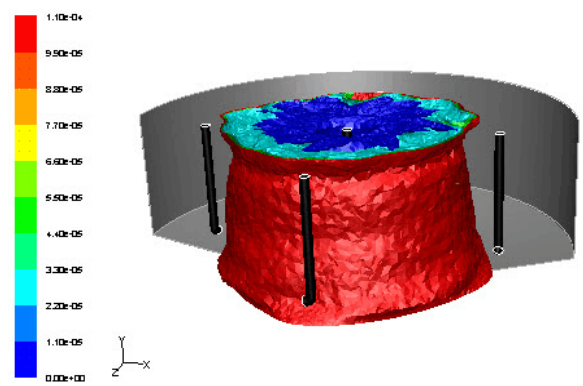


Figure 24: Concentration surfaces after mixing for 60 min. Release of tracer from sludge inlet, Model 3.

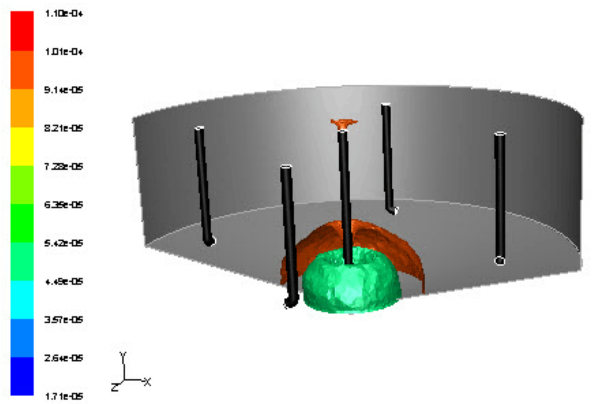


Figure 25: Concentration surfaces after mixing for 246 min. Release of tracer from sludge inlet, Model 3.

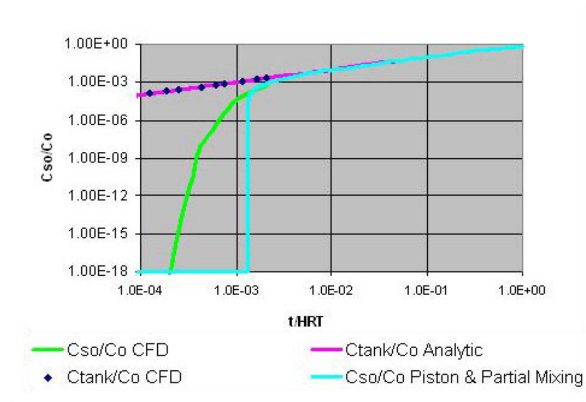


Figure 26: Concentration changes as a result of a step addition of tracer, ω_o = 1.00 at sludge inlet, Model 3, p = 1 - a = 0.0013.

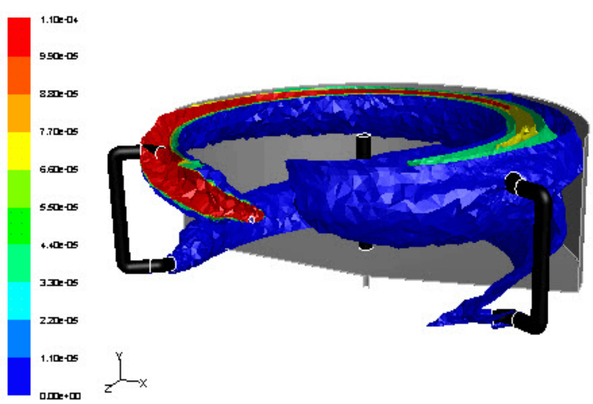


Figure 27: Concentration surfaces after mixing for 1.7 min. Release of tracer from sludge inlet, Model 4.

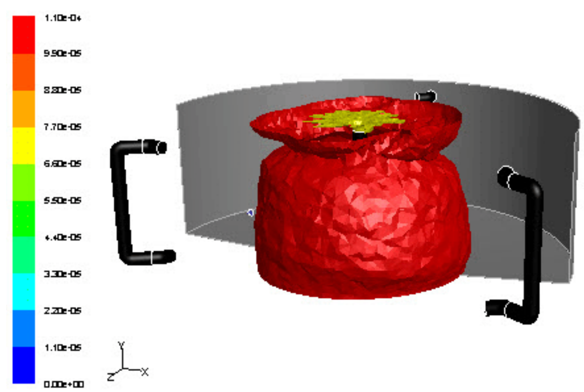


Figure 28: Concentration surfaces after mixing for 27 min. Release of tracer from sludge inlet, Model 4.

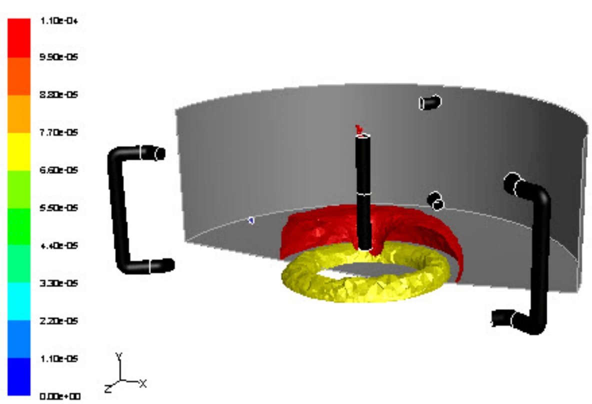


Figure 29: Concentration surfaces after mixing for 34 min, Model 4.

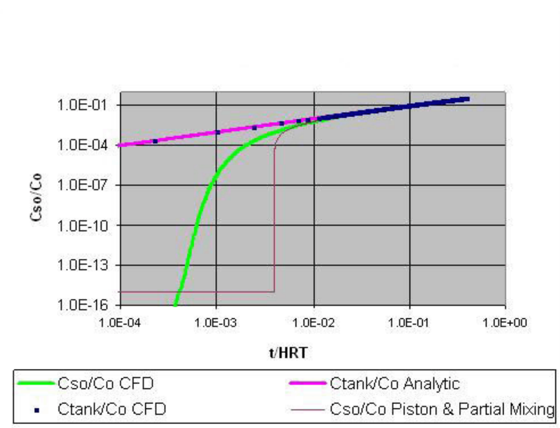


Figure 30: Concentration changes as a result of a step addition of tracer, ω_o = 1.00 at sludge inlet, Model 4, p = 1 - a = 0.004.